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Effects of Solar UV on Spacecraft Charging in Sunlight

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Spacecraft surface charging is determined by the balance of currents. Photoelectron currents from spacecraft surfaces greatly exceed the ambient electron or ion currents and therefore are often of prime importance for charging in sunlight. We present a brief overview of several aspects of spacecraft charging in sunlight. For a conducting spacecraft at geosynchronous altitudes, charging in sunlight is usually up to a few positive volts only. If the spacecraft is in areas where the solar UV is strong and the ambient electron density low, the spacecraft can charge to a few tens of positive volts. For a non-conducting spacecraft at geosynchronous altitudes, the dark side can charge to hundreds or thousands of negative volts as a result of the collection of ambient electrons. There exists a critical electron temperature governing the onset of negative voltage charging. The sunlit side initially tends to charge to low positive volts. The high negative voltage of the dark side may wrap around the sunlit side forming a potential barrier blocking the photoelectrons emitted from the sunlit surfaces. As a result, the sunlit side may also charge to negative voltages. The critical temperature for this differential charging to occur is approximately the same as for eclipse charging. Depending on the spin axis with respect to the sun direction, monopole-dipole or monopole-quadrupole potential distributions may occur. For spacecraft with high surface reflectance, the photons do not deposit enough energy to generate photoelectrons. As a result, the surface can charge to high negative voltages in sunlight without invoking differential charging. In this case, the critical temperature is changed, depending on the reflectance and the photo-emissivity of the surface.

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Nomenclature

A	= dipole strength
A	= area
χ	= ratio of the potentials on the sunlit side and the dark side
ϕ	= surface potential (eV)
I_{ph}	= photoelectron current
J_e	= ambient electron flux
J_{ph}	= photoelectron flux
K	= average potential of the spacecraft
Ly α	= Lyman alpha
n	= surface normal vector
ω	= photon frequency
r	= distance from the center of the spacecraft
R	= surface reflectance
R_0	= surface reflectance for normal incidence
s	= sun direction unit vector
T*	= critical temperature of ambient electrons
θ	= sun angle
UV	= ultraviolet

I. Introduction

Spacecraft surface charging at equilibrium is controlled by the balance of currents according to Kirchhoff's law. Space measurements at geosynchronous altitudes show that the average ambient electron flux is $J_e = 0.115\times10^{-9}$ A/cm^2 [1]. The ambient ion flux J_i is often two orders of magnitude smaller than J_e because of the ion-electron mass difference. Laboratory measurements show that the photoelectron flux emitted from typical surfaces in sunlight is $J_{ph} = 2\times10^{-9}$ A/cm^2 [2]. Therefore, J_{ph} exceeds J_e by a factor of 20 and exceeds J_i by a much larger factor. In spite of this, negative charging can occur in sunlight. This paper presents a brief overview of several aspects of spacecraft charging in sunlight.

II. Conducting Spacecraft

If a spacecraft surface is conducting, its potential is uniform. Summing all currents, one finds that J_{ph} is dominating. Thus the spacecraft voltage ϕ is in positive volts. For photoemission, the most important line in the solar spectrum is the Lyα which is in the UV region. The Lyα line has energy of 10.2 eV. For photoelectrons to leave a surface, they have to pay a 'departure tax' called the work function, W, which is of the order of 4 to 5 eV for most surface materials. Besides, the electrons lose some energy by attenuation inside the solid. Therefore, the photoelectrons have only a few eV in energy. If a spacecraft charges to more than a few positive volts, the photoelectrons can not leave and must fall back to the surface. Thus, the spacecraft can normally charge to a few positive volts only [3,4].

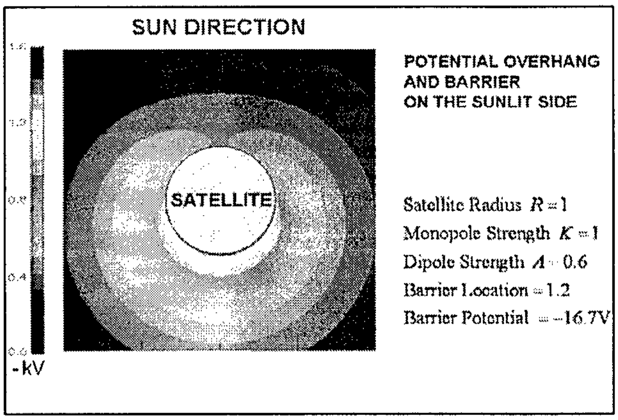

Figure 1. Differential charging in sunlight. *The high negative voltage contours from the dark side wrap around the sunlit side. A potential barrier and a saddle point form near the surface in the area facing the direction.* [*Ref.9*]

III. Non-Conducting Spacecraft

If the spacecraft surfaces are non-conducting, the dark side charges to negative potentials whenever the critical temperature T* [5,6] of the ambient electrons is exceeded. The potentials on the dark side can be hundreds or thousands of

volts negative, depending on the ambient electron energies or temperature. The sunlit side, emitting photoelectrons, initially charges up to at most a few positive volts only. This differential charging occurs only if the spacecraft surfaces are mostly non-conducting. The high negative potential contours may wrap around to the front side and form a potential barrier. The barrier blocks the photoelectrons from escaping, enabling the sunlit side to charge to negative potentials (Figure 1).

\ In such a situation, the potential distribution $\phi(r)$ of the spacecraft can be described by the monopole-dipole [7,8] model. The description is good if the spacecraft is spherical and non-spinning, or if it spins, its spin is parallel to sunlight. The monopole-dipole potential is of the form:

$$\phi(\theta,r) = K\left(\frac{1}{r} - \frac{A\cos\theta}{r^2}\right) \tag{1}$$

where r is the distance from the center of the spacecraft, K the average potential of the spacecraft, θ the sun angle, and A the dipole strength. If the charging voltage of the dark side is much greater than the barrier height, the ratio χ of the potentials on the sunlit side and the dark side has been found to be about χ =1/3 [8, 9, 10, 11, 12] (Figure 2).

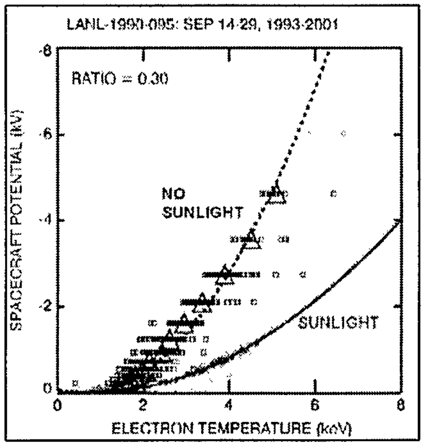

Figure 2 Ratio of observed potentials in sunlight and in darkness. *Surprisingly, the observed value of the ratio agrees with the theoretical prediction of 1/3.* [*Ref.14*]

If the spin axis tilts at a finite angle to sunlight and the spin is faster than the surface capacitance charging time, the potential distribution is symmetrical about the spin axis but not about the sun direction. Tautz and Lai [13,14] found that monopole-quadrupole potential is a good description if the spin axis is perpendicular to sunlight.

$$\phi(\theta,R) = K\left[\frac{1}{r} + \frac{A}{2r^3}\left(3\cos^2\theta - 1\right)\right] \tag{2}$$

For this case, the ratio $\chi \approx 2/5$ [14,15].

Since the charging on the sunlit side is controlled by the charging on the dark side, the critical temperature T* for the onset of spacecraft charging is unchanged in sunlight or in eclipse. This property has been observed to be valid approximately on all LANL geosynchronous satellites observed [10,16].

IV. Spacecraft Surfaces with High Reflectance

If the reflectance is high, much of the incoming photon energy remains in the outgoing photon, transferring very little energy to the surface material for photoemission. As a result, photoemission is reduced for highly reflective surfaces (Figure 3). Lai [17] conjectured that reduced photoemission allows the surface material to charge easily to high negative potentials in sunlight as if in eclipse, provided that the ambient electron temperature exceeds a critical temperature. This mechanism might be a possible explanation of the rapid degradation and stepwise loss of efficiency of Boeing's satellite fleet featuring solar panels flanked by mirrors [17].

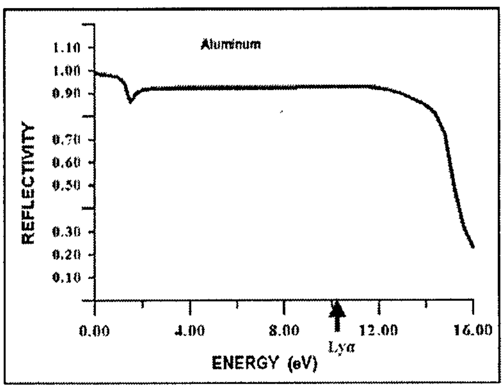

Figure 3 Reflectance of aluminum surface as a function of frequency. *It is nearly 0.9 at Lyman Alpha solar UV spectral line frequency.* [Ref. 17]

Reflectance, mostly neglected in the spacecraft charging literature, should be considered in sunlight charging. Fitting the published data [18,19], Lai and Tautz [11] obtained an empirical formula for the reflectance $R(\omega,\theta)$ as a function of photon incidence angle (Figure 4):

$$R(\omega,\theta) = 1 + (R_0(\omega,0)-1)\cos\theta \tag{3}$$

For a sphere in sunlight, the photoelectron current generated from the sphere [11] is of the form:.

$$I_{ph}(\omega,R) = J_{ph}(\omega,0)\int dA\,\mathbf{s.n}\left(1 - R(\omega,\theta)\right) \tag{4}$$

where J_{ph} is the photoelectron flux emitted, ω the photon frequency, **s** the sunlight direction unit vector, **n** the surface normal unit vector, and dA the integration variable of area. Integrating eq(4), one obtains

$$I_{ph}(\omega,R) = J_{ph}(\omega,0)2\pi r^2 \int_0^{\pi/2} \sin\theta\left(1 - R_0(\omega,0)\right)\cos^2\theta \, d\theta \tag{5}$$

One of the cosine θ factors accounts for the effective cross-section of the spherical surface in sunlight while the other cosine factor comes from the reflectance formula (eq.3). Together the two cosine factors reduce the resultant photoemission significantly. For surfaces at large θ angles with high reflectance, the decrease in photoemission can lead to charging to negative voltages, even without barrier formation (Figure 5). One can see that with decreased photoemission the critical temperature is lowered.

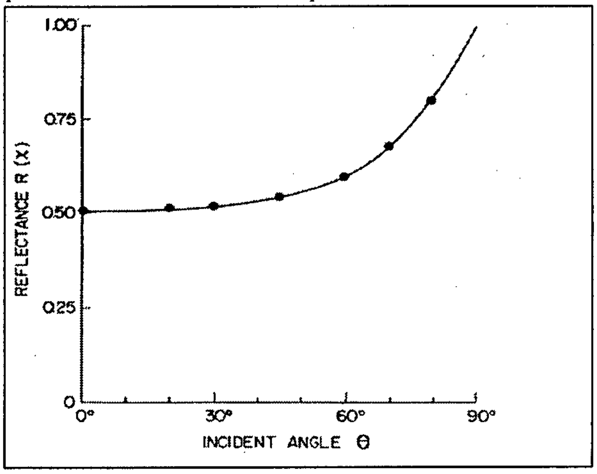

Figure 4 Reflectance of beryllium as a function of incidence angle. *The frequency is that of Lyman Alpha. [Plotted using data of Ref.18].*

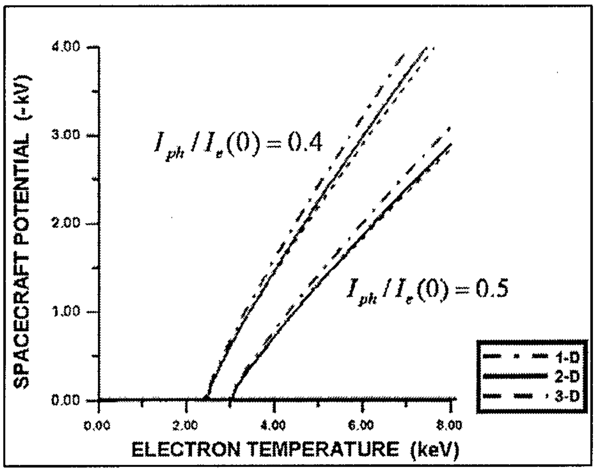

Figure 5 Calculated spacecraft potential using Mott-Smith and Langmuir's orbit limited formulation in 1-D, 2-D, and 3-D. *Reflection reduces the photoelectron flux. Two values of the ratios of photoelectron and ambient electron fluxes are used. The critical temperature for the onset of spacecraft charging varies according to the ratio. [Ref.17]*

V. Conclusion

We have presented a brief overview of several aspects of spacecraft charging in sunlight. The potential of a spacecraft is determined by the balance of currents. The flux of photoemission from a surface in sunlight exceeds the average ambient electron flux by a factor of 20. Therefore, it was widely believed in the early days of spacecraft charging research that negative voltage charging can not occur in sunlight. Indeed, spacecraft with conducting surfaces charge to a few positive volts. If a spacecraft is in regions where the solar UV is strong and the ambient electron density low, charging to tens of positive volts can occur. For non-conducting spacecraft, the dark side charges to negative volts if the ambient electron temperature exceeds a critical temperature. The negative potential contours can wrap around to the sunlit side and form a barrier blocking the photoelectrons. As a result, both sides charge with the sunlit side going less negative. If a spacecraft does not spin or the spin axis is parallel to sunlight, the ratio χ of the potentials on the sunlit and dark sides is 1/3 approximately. This result has been observed in space recently. If the spin axis is at right angles to sunlight, the ratio χ is 2/5 approximately; this value has not been verified by observations. Reflectance reduces photoemission and the photoelectron current and therefore affects spacecraft charging. We stress that reflectance should be included in spacecraft charging calculations and modeling.

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14. ABSTRACT
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